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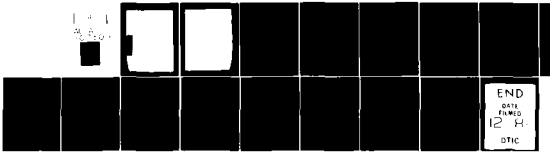

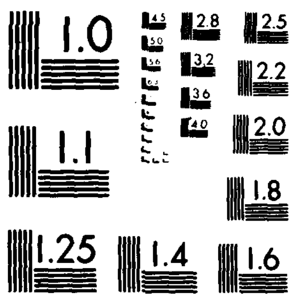

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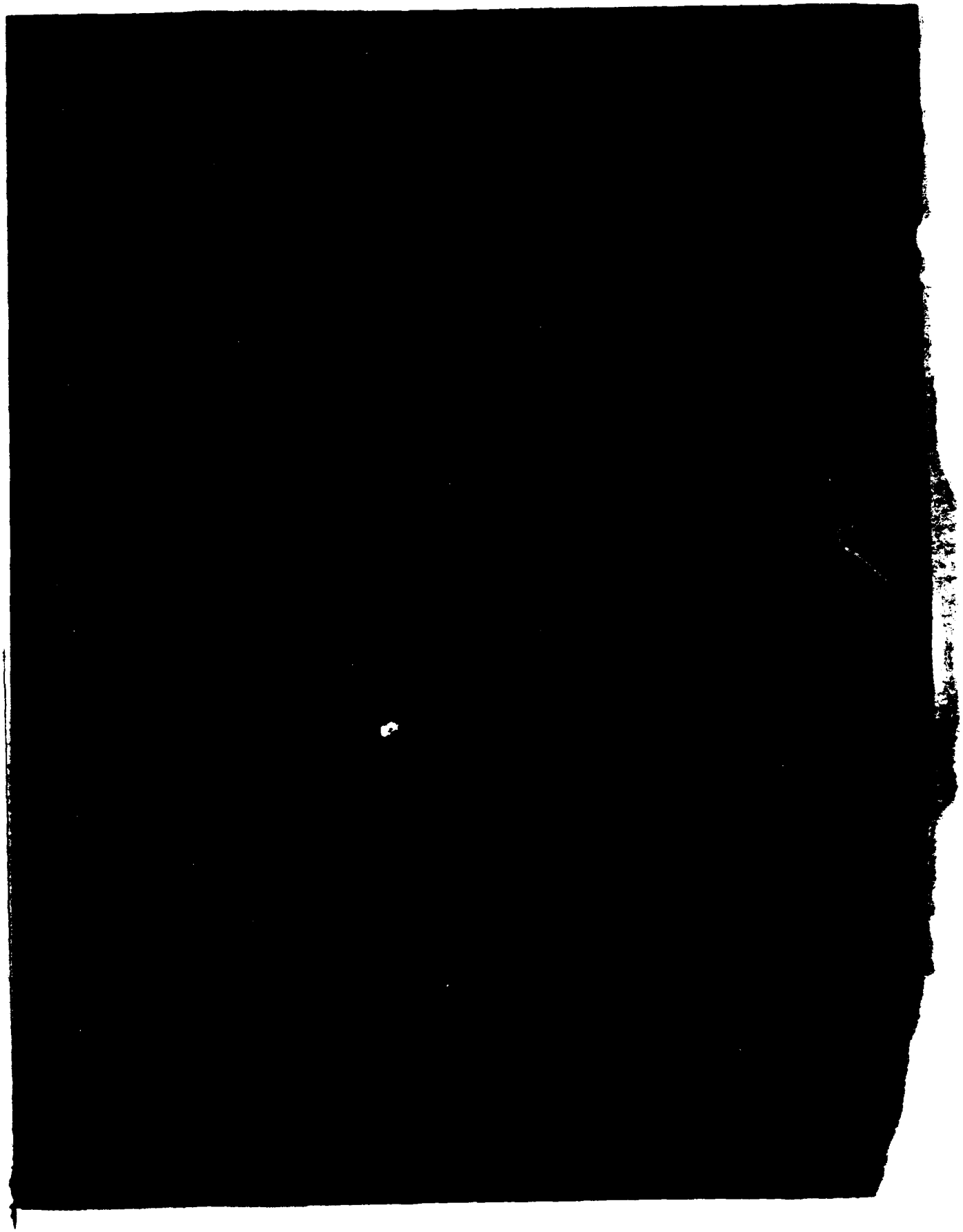

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In recent years upsets caused by single particles passing through Si integrated circuits have been a serious concern in the semiconductor industry. In this report we calculate the threshold voltage shift caused by a single charged particle passing through the SiO_2 layer of a metal-oxide-semiconductor field-effect transistor. This calculation rests on a number of worst-case assumptions: (1) recombination is neglected, (2) charge trapping is taken to be 100-percent efficient, and (3) maximum energy loss per unit path length is assumed. Under these conditions we calculate that permanent failure caused by a single alpha particle is possible in submicrometer-dimension devices.

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CONTENTS

FIGURES

1. INTRODUCTION

In recent years a number of papers have been published on the problem of single-particle-induced upset of small semiconductor memories.[1-5] Upset occurs when a single alpha particle is emitted by a radioactive contaminant in the ceramic packaging. As the alpha particle passes through the silicon chip, it can sometimes generate enough charge to change a stored zero into a one or a one into a zero. When this happens the memory is temporarily scrambled, but it works correctly when it is reset. As devices are further reduced in size, they may become vulnerable to permanent failures from single particles. That is, an alpha particle (or other charged particle) will generate enough trapped charge in the gate oxide to cause a large change in the operating voltage of the device. In this paper we examine the possibility that a single alpha particle might cause the failure of a submicrometer-dimension metal-oxide-semiconductor field-effect transistor (MOSFET).

2. PROCEDURE AND ASSUMPTIONS

We have identified several kinds of particles which have a reasonable probability of hitting a memory element. For each of the particles of interest, we have followed the same basic recipe to calculate the threshold voltage shift of the device. First, we calculate the energy loss as the particle passes through the gate oxide layer. Second, we assume that all the energy loss produces ionization at 18 eV per electron-hole pair. The assumption that ionization is the predominant loss mechanism is widely accepted,[6] and several investigators have reported that the electron-hole pair creation energy is 18 eV.[7,8] We have assumed that charge recombination is negligible. Third, we have assumed that all the electrons are swept out of the oxide "immediately," and all the holes transport to the interface where they are trapped. Obviously this assumption is conservative since the percentage of holes trapped cannot exceed 100 percent, but trapping of 80 percent or more has been reported for commercial devices (with unhardened oxides).[9] Thus, we believe this assumption is reasonable, even though it is clearly a worst case. Fourth, we have assumed that the trapped charge will be uniformly distributed across the area of the device. This assumption may not withstand close examination since the initial distribution will be anything but uniform. However, we will present a preliminary calculation which indicates that most of the charge is distributed in a reasonably uniform fashion. Fifth, from the trapped change distribution, we calculate the change in the threshold voltage of the device, ΔV_T, as a function of device area, A, and oxide thickness, t_{ox}.

[1] T. C. May and M. H. Woods, *Proceedings 1978 International Reliability Physics Symposium (TRPS), IEEE Catalog No. 78CH1294-8PH4*, 33-40.

[2] D. H. Redman, R. M. Sega, and R. Joseph, *Military Electronics/Countermeasures*, **6** (March 1980), 42-47, and (April 1980), 40-48.

[3] D. H. Phillips, *Military Electronics/Countermeasures*, **5** (August 1979), 88-92, and (September 1979), 87-93.

[4] J. F. Ziegler and W. A. Lanford, *Science*, **206** (1979), 776.

[5] J. C. Pickel and J. T. Blandford, *IEEE Trans. Nucl. Sci.*, **NS-27** (1980), 1006.

[6] R. D. Evans, *The Atomic Nucleus*, McGraw-Hill, New York (1955).

[7] G. A. Ausman and F. B. McLean, *Appl. Phys.*, **26** (1975), 173-175.

[8] O. L. Curtis, J. R. Srour, and K. Y. Chiu, *J. Appl. Phys.*, **45** (1974), 4506.

[9] R. Freeman and A. Holmes-Siedle, *IEEE Trans. Nucl. Sci.*, **NS-25** (1978), 1216.

3. PARTICLES OF INTEREST

We have considered four sources of charged particles which could cause single-particle permanent failures. These sources have all been discussed in the literature in connection with soft errors.[1,5,10] They are the following:

(1) a secondary alpha particle produced by the reaction of a thermal neutron with B^{10},

(2) a secondary alpha particle produced by the reaction of a 14-MeV neutron with Si^{28},

(3) an alpha particle from a radioactive contaminant in the circuit packaging, and

(4) a cosmic ray proton.

In the first case, a thermal neutron hits a B^{10} dopant atom and an alpha particle with an energy of about 1.8 MeV is emitted. A Li^7 atom with a recoil energy of about 1.0 MeV is also produced. The cross section for this reaction is about 3840 barns/atom.* For a p-type substrate with a doping density on the order of 10^{16} B/cm^3, there would be on the order of 10^{12} B^{10}/cm^2 within an alpha particle range of the SiO_2 layer. If we assume 1 percent of the surface is covered by active devices and make some reasonable estimate of the solid angle subtended by these devices, we estimate that one alpha particle will hit an active device for each 10^{11} thermal neutrons/cm^2 incident. Guenzer[10] looked for soft errors resulting from this reaction but did not detect any. He concluded that the energy of the alpha particle was too low to produce enough charge to cause an upset. However, one can see from figure 1 that the energy of the alpha particle from this reaction is very nearly optimum for producing hard failures.

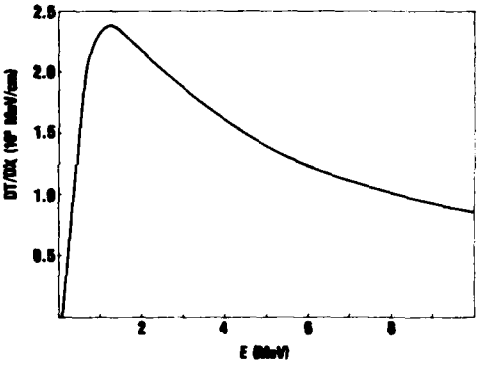

Figure 1. Stopping power as a function of energy for alpha particles in SiO_2.

[1] T. C. May and M. H. Woods, *Proceedings 1978 International Reliability Physics Symposium (TRPS), IEEE Catalog No. 78CH1294-8PH4*, 33-40.

[2] D. H. Redman, R. M. Sega, and R. Joseph, *Military Electronics/Countermeasures*, **6** (March 1980), 42-47, and (April 1980), 40-48.

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[10] C. S. Guenzer, R. G. Allas, A. B. Campbell, J. M. Kidd, E. L. Peterson, N. Seeman, and E. A. Wolicki, *IEEE Trans. Nucl. Sci.*, **NS-27** (1980), 1425.

*(barns) × 10^{-24} = (cm^2)

[10] C. S. Guenzer, R. G. Allas, A. B. Campbell, J. M. Kidd, E. L. Peterson, N. Seeman, and E. A. Wolicki, *IEEE Trans. Nucl. Sci.*, **NS-27** (1980), 1425.

[11] H. Enge, *Introduction to Nuclear Physics*, Addison-Wesley (1966).

[12] R. H. Dennard, F. H. Gaensslen, Hwa-Nien Yu, V. L. Rideout, E. Bassous, and A. R. LeBlanc, *IEEE J. Solid State Circuits*, **SC-9** (1974), 256.

In the second case, a 14-MeV neutron hits a Si^{28} atom producing an alpha particle, a Mg^{25} atom, and about 11 MeV in excess energy. The cross section for this reaction is only about 0.055 barns/atom, but the number of Si atoms within alpha particle range of the oxide layer is on the order of 10^{20} per square centimeter. Thus the probability of a neutron producing an alpha particle capable of reaching the oxide is on the order of 10^{-6}, and the probability of a neutron producing a "hit" is on the order of 10^{-8} (assuming 1-percent coverage again). This result is more or less consistent with results reported by Guenzer for soft-error generation in various random access memories.[10] The alpha particle produced by this reaction has a much higher than optimum energy for producing hard failures, but the alpha particle will have to transport through several micrometers or tens of micrometers of Si to reach the oxide. For this reason, a distribution of alpha particle energies will be observed at the oxide, and some reasonable fraction of them will probably fall in the optimum energy range. In any event, the stopping power at the initial energy of the alpha particle is only a factor of three or so below the maximum stopping power (fig. 1) for an alpha particle. Thus we conclude that this reaction may cause permanent failures.

In the third case, alpha particles from radioactive contaminants have been observed to cause upset in many different kinds of devices. We know from the number of upset engineers that the alpha particles are reasonably abundant. Generally these particles have an energy of 5 or 6 MeV which is not optimum for producing hard failures, but the stopping power is down by about half from the maximum.

In the fourth case, we have briefly considered cosmic ray protons. These particles have a lower energy transfer than alpha particles. While they might eventually cause permanent failures, it is clear that alpha particles are a more serious problem than protons. For this reason, we have generally concentrated on alpha particles and neglected protons.

4. CALCULATIONS AND RESULTS

The basic stopping power formula for a heavy charged particle (which can be found in any basic nuclear physics book[6,11]) is

$$-\frac{dT}{dx} = \frac{z^2 e^4 Z N}{4\pi\varepsilon_0^2 m_0 v^2}\left(\ln\frac{2 m_0 v^2}{I} + \text{relativistic corrections}\right). \quad (1)$$

where

T is the kinetic energy of the incident particle,

z is the effective charge of the incident particle,

Z is the atomic number of the target material,

N is the number of target atoms per unit volume,

e is the electron charge,

ε_o is the free space permittivity,

m_o is the electron rest mass,

[10] C. S. Guenzer, R. G. Allas, A. B. Campbell, J. M. Kidd, E. L. Peterson, N. Seeman, and E. A. Wolicki, IEEE Trans. Nucl. Sci., **NS-27** (1980), 1425.

[6] R. D. Evans, The Atomic Nucleus, McGraw-Hill, New York (1955).

[11] H. Enge, Introduction to Nuclear Physics, Addison-Wesley (1966).

v is the velocity of the incident particle, and

I is the mean ionization potential (130 eV for SiO_2).

For particles of practical interest, the relativistic terms can be neglected. Since the range of most heavy charged particles is much greater than the thickness of the oxide layer, the stopping power is essentially constant through the oxide. Because of the charge transfer effect, the effective charge of the incident particle is a function of its velocity. Measurements of the effective z as a function of velocity have been performed by several investigators for protons and alpha particles, and the results have been collected by Evans.[6] If we include the velocity dependence of z in equation (1), we calculate the stopping power for alpha particles shown in figure 1. The worst case for producing permanent failures is at relatively low energies around 1.5 MeV. To calculate the threshold shift, we write $\Delta V_T = Q/C$, where

$$Q = \left| -\frac{dT}{dx} \right| (a)(\ell_{ox}) \left(\frac{1}{18\ eV/\epsilon^+} \right) \times \left(1.6 \times 10^{-19} \frac{coul}{e^+} \right) \frac{1}{A} f_t f(E) \quad , \qquad (2)$$

and $C_{ox} = \varepsilon\varepsilon_o/\ell_{ox}$. In these expressions, the following definitions have been used:

$-\frac{dT}{dx}$ is the energy loss (eV/cm),

ℓ_{ox} is the oxide thickness (cm),

a is a geometrical correction factor to allow for the oblique angle of incidence of a typical particle ($a = 1/\cos\theta$),

A is the active area of the memory element (cm^2),

ε is the relative permittivity of SiO_2 (taken to be 3.85),

ε_o is the permittivity of free space, 8.85×10^{-14} F/cm,

f_t is the fraction of holes reaching the interface which are trapped there, and

f(E) is the fraction of holes which escape recombination where they are created—in general a function of the applied field E.

As indicated previously, in the discussion which follows, we assume that both f_t and f(E) are equal to one. If we assume the "average" particle to be incident at 45°, then $a = 1/\cos 45° = 1.404$, and we can rewrite the above expressions as follows:

$$\Delta V_T = \left(3.65 \times 10^{-8} \frac{V \cdot cm}{eV} \right) \frac{\ell_{ox}^2}{A} \left| \frac{dT}{dx} \right| \qquad (3)$$

The threshold voltage shift for a wide range of device sizes and oxide thicknesses is plotted in figure 2, for a worst-case alpha particle.

The largest device size represented in figure 2 is 1 by 1 μm and the smallest device is 0.1 μm^2. In Dennard's paper on scaling laws,[12] he discussed the scaling down of a 5 by 5 μm device to 1 by 1 μm. We have taken that discus-

[6] R. D. Evans, *The Atomic Nucleus*, McGraw-Hill, New York (1955).

[12] R. H. Dennard, F. H. Gaensslen, Hwa-Nien Yu, V. L. Rideout, E. Bassous, and A. R. LeBlanc, IEEE J. Solid State Circuits, **SC-9** (1974), 256.

sion as our starting point in this study. If we insert, in equation 2, $|dT/dx| = 2.4 \times 10^9$ eV/cm, A = 10^{-8} cm^2, and Dennard's value of t_{ox} = 35 nm we get $\Delta V_T \approx 0.11$ V. This threshold shift is enough to cause permanent failure in some NMOS (nitride MOS) circuits. Thus we conclude that if our conservative assumptions hold up, a single alpha particle can cause the permanent failure of a device.

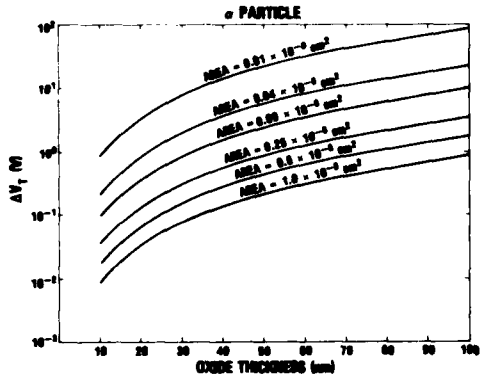

Figure 2. Threshold voltage shift as a function of oxide thickness from a worst-case alpha particle incident on devices of various areas.

Goals of the Very-High-Speed Integrated Circuit (VHSIC) program which have been widely discussed include devices with 0.05-μm minimum dimensions. For a device 0.5 by 0.5 μm with an oxide thickness of 20 or 25 nm, one can see from figure 2 that a worst-case alpha particle will cause a shift of $\Delta V_T = 0.18$ V.

Elliot et al[13] discuss devices as small as 0.25 μm square with an oxide thickness of 24 nm. For such a device, we calculated that a worst-case alpha particle will cause a shift ΔV_T = 0.81 V. This shift is large enough to cause failure in many kinds of devices. Some contemporary NMOS devices can survive a shift of only 0.1 V. There are tradeoffs involved in setting this tolerance, but in general the tolerable threshold shift will scale down in rough proportion to the device size. Thus one can see that the threshold shift caused by a single alpha particle could be a serious problem for submicrometer devices.

5. DISCUSSION

Some reservations about the preceding analysis should be mentioned. First we assumed that one hole will be trapped at the Si-SiO_2 interface for each 18 eV of energy absorbed in the oxide. This is equivalent to neglecting recombination or taking f(E) = 1 in equation (2). However, the literature suggests that this assumption is probably not very good.[14] Presently we are preparing experiments to measure the recombination function f(E). We expect the yield to be reduced by a factor of perhaps two or more from what we have assumed in the preceding analysis for fields of practical interest. We are also planning to apply some existing theoretical models[14-17] to our experimental results in order to gain the ability to predict the charge yield for other kinds of radiation.

Second, we have assumed that the trapped charge is distributed uniformly across the active area of the device. However, the region where charge is created initially is likely to be only a few tens of nanometers in diameter. Transport (and diffusion) will be influenced by the applied field, the mutual repulsion of the holes, and the field between source and drain. A detailed calculation of the spatial distribution of trapped charge is complicated and beyond the scope of this report. However, we have carried out a preliminary particle-pushing calculation to get a rough idea of the

[13] *M. T. Elliot, M. R. Splinter, A. B. Jones, and J. P. Reekstin, IEEE Trans. Electron Devices,* **ED-26** *(1979), 469.*

[14] *A. Mozumder and J. L. Magee, Radiation Research,* **28** *(1966), 203-214.*

[15] *G. Jagge, Ann. Phys. (Leipzig),* **42** *(1913), 303.*

[16] *L. Onsager, Phys. Rev.,* **54** *(1938), 554.*

[17] *K. M. Hong and J. Noolandi, J. Chem. Phys.,* **69** *(1978), 5026.*

uniformity of charge distribution. We assumed a normally incident alpha particle passed through a 100-nm oxide, creating about 1300 holes in a cylinder of 10-nm radius. The holes are allowed to "hop"[18] parallel to the total field (applied bias and mutual repulsion of the holes) until they reach the interface where they are trapped. The resulting charge distribution at the interface is shown in figure 3. The dotted line represents our assumption of a uniform charge distribution. One can see that although the density is much higher than this assumption in a small area near the origin, the assumption is not unreasonable for most of the charge and most of the active area. Since the diameter of the alpha-particle footprint is roughly 0.4 μm, the assumption of uniform density is probably reasonable for devices 0.5 μm and smaller, although it seems a little dubious for 1-μm devices. We are refining our calculation and also preparing a series of experiments to shed more light on the question of the charge distribution at the interface.

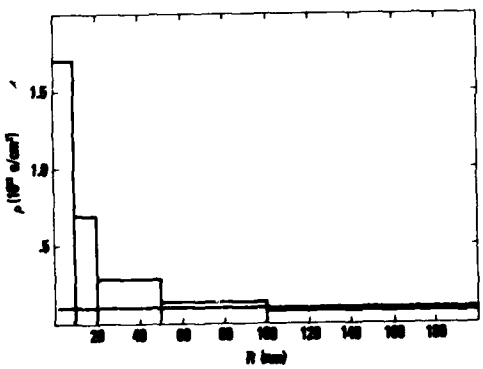

Figure 3. Calculated charge distribution at the interface for a 2-MeV alpha particle normally incident on a 100-nm-thick SiO_2 film.

We would also like to point out a number of steps which can be taken to prevent single-particle-induced permanent failures. First, devices can be manufactured with radiation-hard oxides. We have indicated that for unhardened oxides, trapping fractions f_t greater than 80 percent have been reported,[9] but hardened oxides with f_t as low as one or two percent have also been reported.[19] Second, ΔV_T is proportional to the square of the oxide thickness in our analysis. The trend in the industry is to thinner oxides, which will mean lower ΔV_T and hence harder devices in the future. Third, the thermal neutron reaction with B^{10} can be eliminated by removing B^{10} from the device. Thus, the technology already exists to build devices hardened against single-particle failure.

6. CONCLUSIONS

In summary, we calculate that a single alpha particle can cause a permanent failure of an MOS memory element if we assume that charge recombination can be neglected, all holes are trapped at the interface, and the trapped holes are distributed uniformly across the device. These assumptions are conservative, but they are probably not outrageous. Thus we conclude that single-particle-induced permanent failures may be observed as submicrometer devices come into production, unless steps are taken to prevent them.

[18] F. B. McLean, H. E. Boesch, and J. M. McGarrity, IEEE Trans. Nucl. Sci., **NS-23** (1976), 1506.

[9] R. Freeman and A. Holmes-Siedle, IEEE Trans. Nucl. Sci., **NS-25** (1978), 1216.

[19] J. M. McGarrity, IEEE Trans. Nucl. Sci., **NS-27** (1980), 1739.

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